MEASURED AND PREDICTED EVAPOTRANSPIRATION OF GRAIN SORGHUM

GROWN WITH FULL AND LIMITED IRRIGATION IN THREE HIGH PLAINS SOILS

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ABSTRACT

Water conservation in irrigated agriculture of the semi-arid Great Plains relies on accurate prediction of crop water use to obtain the greatest benefit from declining irrigation water supplies. One method for estimating crop water use applies crop specific coefficients to adjust reference evapotranspiration (ET_o). We compared daily measured evapotranspiration (ET_m) of limited and fully irrigated grain sorghum to modeled ET (ET_c) calculated using single and dual crop coefficients (K_c) and a grass-based ET_o. The dual K_c procedure contained separate coefficients for crop transpiration, soil water evaporation, and crop water stress, as compared with one coefficient in the single K_c procedure. Short season grain sorghum was grown in lysimeters on deck scales containing monolithic soil cores of either Pullman, Ulysses, or Amarillo soil located in a rain shelter facility. With the dual K_c procedure, the difference during the season between cumulative ET_c and ET_m varied from 2 to around 70 mm, and by the end of the season the maximum difference in all treatments was about 70 mm, or 15%, with an average of 4%. The single K_c procedure underestimated final cumulative ET_m in the fully irrigated treatments by an average of 9%. The dual K_c procedure was sensitive to errors in required initial specifications for soil water balance and crop response to water stress in the limited irrigation treatments, but overall it improved water use predictions compared with the single K_c procedure.
KEYWORDS. Crop coefficient, Irrigation scheduling, Lysimeters, Model evaluation

INTRODUCTION

Agricultural producers in the semi-arid Great Plains must maximize water use efficiency as irrigation water supplies decline and pumping costs increase. One approach has been to schedule irrigation timing and amounts based on accurate predictions of crop water use. Measured crop evapotranspiration (ET_m) routinely has been estimated from reference evapotranspiration (ET_o) combined with crop coefficients (K_c) (Jensen et al., 1970). The crop coefficient is an empirical ratio of ET_m to ET_o. It relates ET_o, which is based on ET of a reference crop, to ET_m by integrating the crop- and soil-specific characteristics that differ from those used for the reference crop, such as crop height (which affects crop aerodynamic resistance to heat and vapor transport), crop-soil resistance to water loss (affected by crop stomatal characteristics and soil texture), and soil albedo. Calculation of ET by this method often used procedures outlined by Doorenbos and Pruitt (1975) in a publication commonly known as FAO-24 (United Nations Food and Agriculture Organization's Irrigation and Drainage Paper Number 24).

This procedure was updated in FAO-56 (Allen et al., 1998), and uses the Penman-Monteith combination reference ET_o method with grass as the reference crop. In addition to containing the single K_c approach which combines crop transpiration and soil water evaporation into one value, the updated procedure includes procedures for calculating a dual K_c, which has separate

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coefficients for crop transpiration (K_{cb}, or basal crop coefficient), soil water evaporation (K_e), as well as crop water stress (K_s). The need to have separate coefficients for soil water evaporation and water stress was recognized early in the development of the crop coefficient procedure (Jensen et al., 1971).

The dual K_c procedure is recommended for daily calculations of ET which require more accurate values of K_c. The procedure adjusts the K_{cb} for crop growth stage and daily variations in meteorological conditions, and combines it with fluctuations in K_e due to rainfall and irrigation and K_s due to a reduction in soil water content below the level that induces crop water stress. Calculation of K_e requires specification of soil water holding characteristics such as field capacity (FC), permanent wilting point (PWP), readily evaporable water (potential evaporation) and, from the specified soil surface depth from which surface evaporation occurs, the total evaporable water. Calculation of K_s additionally requires rooting depth which, when combined with FC and PWP, determines total available water, and the percentage of the total available water that can be used before the crop experiences water stress, or readily available water.

The objective of this research was to compare daily ET_c calculated by both single and dual crop coefficient procedures with lysimetrically measured ET_m of short-season grain sorghum grown under full and limited irrigation in three soil types. This would help determine if the more complicated dual K_c procedure improved prediction of crop water use compared with the simpler single K_c procedure.

MATERIALS AND METHODS

Agronomy

A short season grain sorghum hybrid 'PIO-8699'** was grown at a plant density of 16 plants m^{-2} in 1997, 1998, and 1999 at the USDA-ARS Soil-Plant-Environment Research (SPER) facility at Bushland, TX. The facility had lysimeters (1 m wide by 0.75 m long by 2.4 m deep) which contained monolithic cores of either Pullman clay loam, Ulysses clay loam, or Amarillo fine sandy loam. Deck scales (Weigh-Tronix Model DS30x40-10K) under the lysimeters used in the analysis measured daily changes in mass balance. There were two replicates of each soil type/irrigation treatment combination in 1997 and 1998, and three in 1999. All treatments received 19 g N m^{-2} prior to planting. Irrigation treatments were 110% and 70% of measured ET in 1997, and 100% and 50% of measured ET in 1998 and 1999. Soil water content was monitored using neutron scattering. At the beginning of the experiments, the Pullman and Amarillo soil cores were at about 100% of field capacity in 1997 and 1998 and at about 65% in 1999. The Ulysses cores were at about 75% of field capacity in 1997 and 1998 and 50% in 1999. Weekly irrigations were volumetrically measured and applied by hand using buckets. The SPER facility had a rain shelter which allowed control of the lysimeter water balance. The shelter remained 15 m north of the research area until needed. Wind direction was predominately from the south-southwest. The lysimeter area was surrounded by similarly cropped grain sorghum for about 30 to 35 m in the prevailing wind direction. About 450 m of dryland grain sorghum was south of the SPER facility, and a heterogeneous landscape of grassland, playa, and irrigated and dryland cropland extended more than 1700 m to the southwest.

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Crop Coefficients

Input parameters for calculation of ET_c for both full and limited irrigation treatments using the dual K_c procedure are shown in Table 1. Additional required inputs were length of the four crop growth stages (initial, development, mid-season, end season) and the K_{cb} for each growth stage.

Table 1. Soil parameters used in calculating the dual K_c, including field capacity (FC), permanent wilting point (PWP), crop rooting depth (Z_r), depth of soil contributing to second stage evaporation (Z_e), total evaporable water (TEW), readily evaporable water (REW), total available water (TAW), readily available water (RAW), and fraction of TAW that can that can be depleted before water stress occurs..

	FC	PWP	Z_r	Z_e	TEW	REW	TAW	RAW	p
	(m^3/m^3)	(m^3/m^3)	(m)	(m)	(mm)	(mm)	(mm)	(mm)	(mm/mm)
Pullman	0.34	0.22	2.0	0.15	33	10	240	121	0.55
Ulysses	0.35	0.14	2.0	0.15	42	10	420	336	0.80
Amarillo	0.26	0.13	2.0	0.10	20	9	260	143	0.55

Lengths of the crop growth stages were established by plotting measured K_c (ET_m/ET_0) vs. day of year as shown in FAO-56 (p. 158). Soil parameters required included permanent wilting point (PWP), field capacity (FC), readily evaporable water (REW), and depth of soil contributing to soil water evaporation (Z_e). The parameters of FC, PWP, and Z_e determined total evaporable water (TEW), and FC, PWP, and crop rooting depth (Z_r) determined the total available water (TAW). The parameters TAW and its fraction of water that can be depleted before water stress occurs (p) were used to calculate readily available water (RAW). Many of these parameters were determined in prior tests associated with the SPER facility, and were similar to those recommended in FAO-56. The K_{cb} values were adjusted for climatic effects.

Daily ET_c of the full irrigation treatments was also modeled using the single K_c procedure in FAO-56. Crop coefficients used in establishing the crop coefficient curve for the four crop growth stages were those recommended in FAO-56 for grain sorghum. The initial K_c value was calculated from the dual K_c procedure as the sum of the soil water evaporation and basal crop coefficient of 0.15. The mid-season K_c was set at 1.1 and the end season K_c at 0.55, and were adjusted for climatic effects during those growth stages.

Calculation of ET_0

Data for the calculation of ET_0 were gathered at a weather station with irrigated, cool season grass about 1000 m from the SPER facility. Weather station instrumentation was described fully in Dusek et al. (1987). Calculation of ET_0 in general followed FAO-56 guidelines. Differences between FAO-56 calculations for ET_0 and those used in this study include soil heat flux (Wright, 1982) and calculated rather than constant values for the latent heat of vaporization and air density (Jensen et al., 1990).

RESULTS AND DISCUSSION

Total seasonal ET_c predicted by both the single and dual K_c procedures tended to be lower than total seasonal ET_m in all three years (Table 2). Using the single K_c procedure for the full irrigation treatments, the difference between total seasonal ET_m and ET_c ranged from +1% (7 mm) to -13% (92 mm), with an average of about 9%, or 60 mm. The best performance by the

Table 2. Measured and predicted total seasonal ET and their difference using dual and single crop coefficients.

| | 1997 | | | 1998 | | | 1999 | | |
| | Meas. | Pred. | Dif. | Meas. | Pred. | Dif. | Meas. | Pred. | Dif. |
Treatment	(mm)	(mm)	(%)	(mm)	(mm)	(%)	(mm)	(mm)	%
Full Irrigation (Dual K_c)									
Pullman Clay Loam	665	661	- 1	653	634	- 3	560	562	< 1
Ulysses Clay Loam	710	685	- 4	659	645	- 2	578	573	- 1
Amarillo Sandy Loam	581	610	+ 5	613	580	- 5	548	539	- 2
Limited Irrigation (Dual K_c)									
Pullman Clay Loam	595	590	- 1	527	516	- 2	476	406	-15
Ulysses Clay Loam	694	646	- 7	511	518	+1	468	421	-10
Amarillo Sandy Loam	613	576	- 6	471	477	+1	433	404	- 7
Full Irrigation (Single K_c)									
Pullman Clay Loam	665	608	- 9	653	574	-12	560	512	- 9
Ulysses Clay Loam	710	618	-13	659	577	-12	578	519	-10
Amarillo Sandy Loam	581	588	+ 1	613	549	-10	548	506	- 8

single K_c procedure was in the full irrigation treatment in the Amarillo soil in 1997, which accurately modeled ET_m throughout the season unlike that modeled using the dual K_c procedure. In general, cumulative ET_c modeled using the single K_c procedure remained below cumulative ET_m throughout the season. The difference between total seasonal ET_m and ET_c modeled using the dual K_c procedure ranged from <-1% (2 mm) to -15% (70 mm), with an average across all treatments of about 4%, or 20 mm. The dual K_c procedure tended to overestimate ET_m early in the season, and underestimate it later. Although this compensation resulted in predicted and measured seasonal totals that were often similar, the difference during the season could be as high as 60 mm. The errors in predicting of ET_m appeared to be related to soil water evaporation following an irrigation, with predicted K_c ($K_{cb}+K_e$) being larger than measured K_c (ET_m/ET_o) initially, and lower than measured during mid and late season crop growth stages (Fig. 1).

The performance of the dual K_c procedure in predicting ET_m on a daily basis can be seen in the regressions of daily ET_m to ET_c in Table 3. The high root mean square error (RMSE) values were in the treatments where ET_m was substantially both over-predicted early
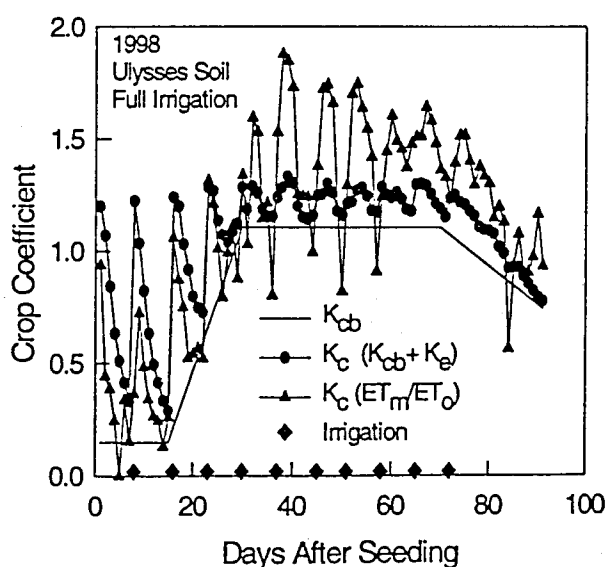

Figure 1. Measured K_c (ET_m/ET_o) and modeled K_c ($K_{cb}+K_e$) with irrigations.

Table 3. Linear regression of measured ET and modeled ET values using the dual crop coefficient procedure for the full irrigation and limited irrigation treatments..

Treatment	1997				1998				1999			
	b†	a	RMSE	r^2	b	a	RMSE	r^2	b	a	RMSE	r^2
		(mm/d)	(mm/d)			(mm/d)	(mm/d)			(mm/d)	(mm/d)	
Full Irr.												
Pullman	1.01	0.0	1.7	0.74	1.14	-0.8	1.6	0.72	1.04	-0.2	1.2	0.86
Ulysses	0.98	0.3	2.2	0.61	1.27	-1.8	1.9	0.66	1.17	-0.9	1.3	0.86
Amarillo	0.92	0.2	1.4	0.79	1.09	-0.2	1.7	0.72	1.06	-0.2	1.4	0.83
Lim. Irr.												
Pullman	0.80	1.0	1.6	0.71	0.74	1.6	1.3	0.69	0.78	1.4	1.2	0.76
Ulysses	0.92	0.9	2.2	0.60	0.82	1.0	1.7	0.64	0.87	1.0	1.2	0.79
Amarillo	0.95	0.6	1.6	0.75	0.77	1.1	1.5	0.67	0.88	0.8	1.1	0.80

·† The regression equation takes the form ET_c (measured)= b *ET_c (modeled) + a.

in the season, and under-predicted later in the season. Predicted and measured values were similar throughout the season in the treatments with RMSE values less than 1.5 mm/d.

The error in predicting final seasonal ET_m using the dual K_c procedure tended to be greater in the limited irrigation treatments, which required not only accurate knowledge of the soil hydraulic characteristics but also the amount of soil water depleted below field capacity at planting. In 1997 and 1998, the treatments began with soil water at or near field capacity, so errors in specification of the initial soil water contents were not a factor. In 1999, when soil water for all treatments was less than field capacity, errors in the final seasonal ET_c may have been increased by errors in beginning soil water contents. The algorithm used to predict the decline in ET due to water stress may also have contributed to errors in estimating crop water use. The largest error in predicting final season ET_m using the dual K_c procedure occurred with the limited irrigation treatment in the Pullman soil in 1999 (Fig. 2). Measured and modeled ET began to diverge at about 50 DAS, when predicted soil water contents fell below RAW and the soil water stress factor (K_s) reduced the K_{cb} rapidly. Kerr et al. (1993) pointed out that such algorithms lead to large adjustments with little change in 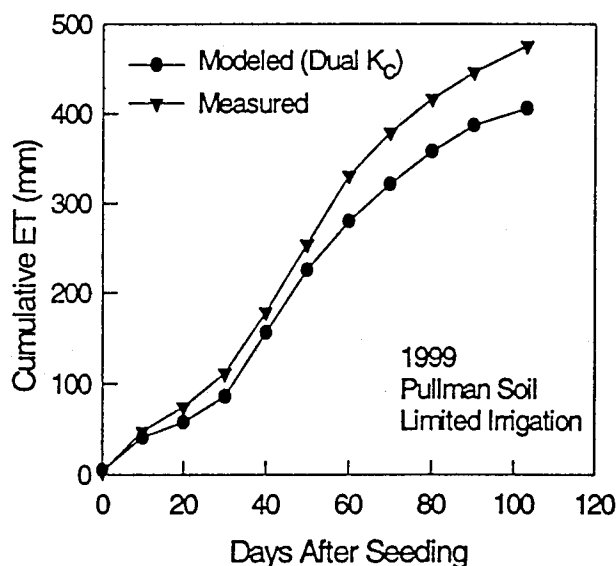soil water content. Shaozhong et al. (2000) suggested that K_s could also be obtained from the ratio of ET_m of a limited irrigation treatment to ET_m of a fully irrigated one. Fig. 3 shows the ratio of the limited to fully irrigated

Figure 2. Measured and modeled ET.

treatments in the Pullman soil as well as the calculated K_s beginning about 50 DAS in 1999. The K_s of the dual K_c procedure had a more negative slope than the ratio of measured ET of the limited irrigation and fully irrigated treatments, which produced a final seasonal ET that was 70 mm lower than the measured value.

CONCLUSIONS

The dual K_c procedure generally improved the prediction of crop water use compared with the single K_c procedure in the fully irrigated treatments. Accurate prediction of ET_c for the limited irrigation crops required substantial knowledge of soil water holding characteristics and initial soil water contents, which

Figure 3. Water stress coefficients (K_s) determined from the ratio of limited to full irrigation ET (ET_m)/ET_m) and modeled from the dual $K_c$procedure for the 1999 limited irrigation treatment in the Pullman soil.

may not be readily available. The algorithm used to model the response of grain sorghum ET to declining soil moisture water stress may not adequately predict greater declines in ET than that measured when soil water supplies are severely limited.
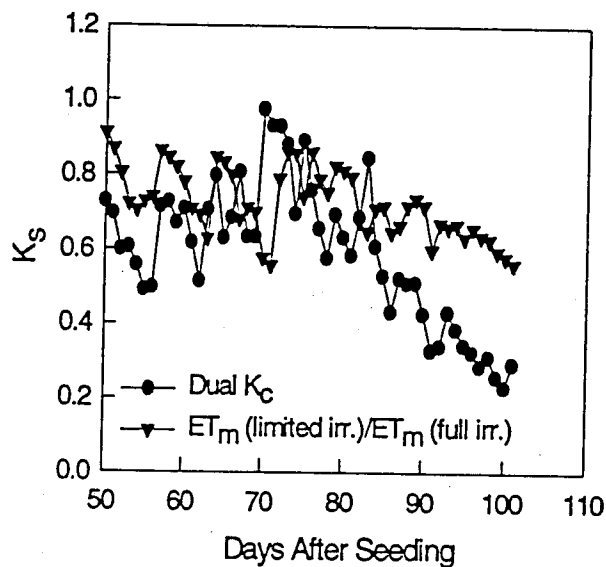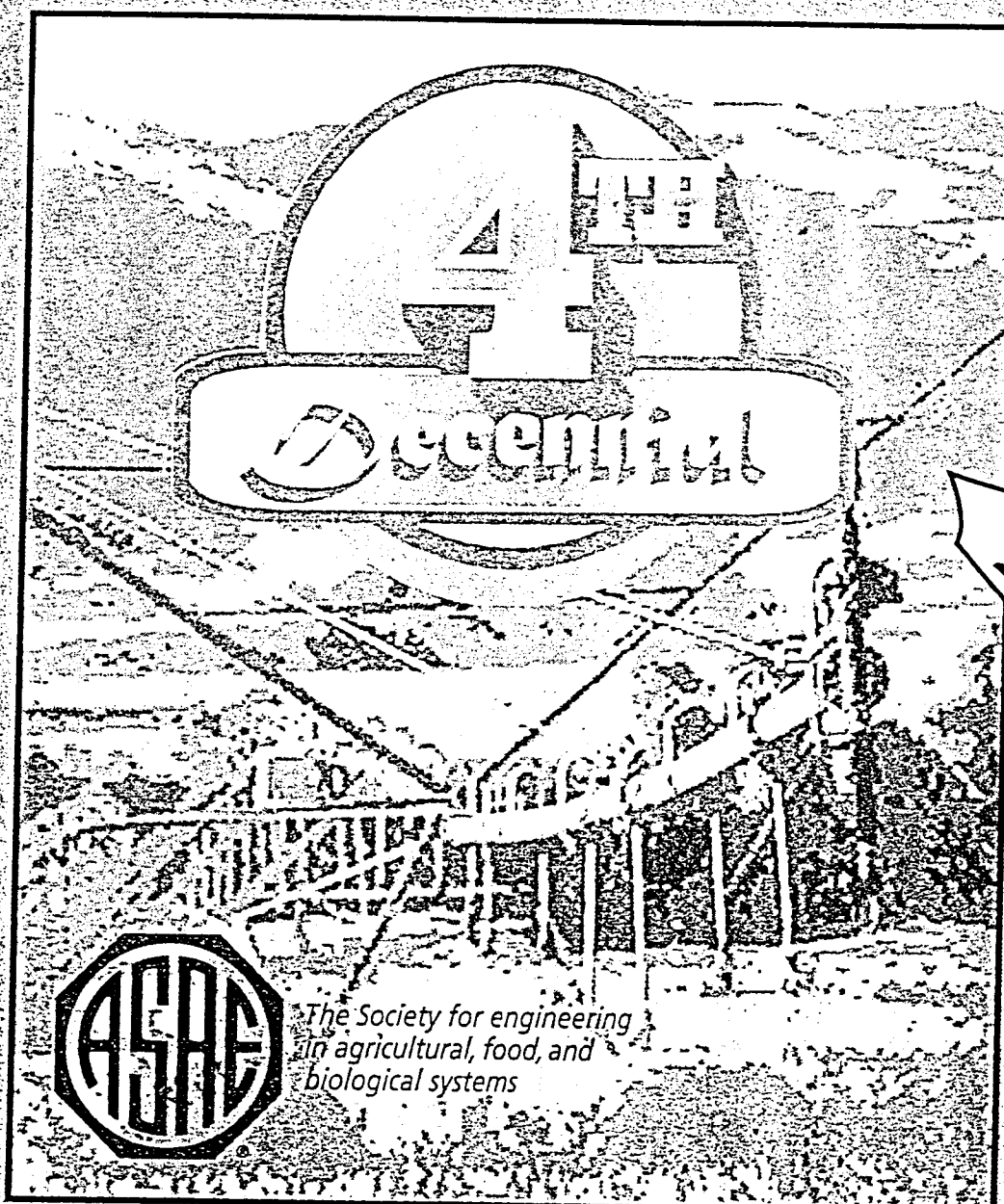
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